UV OBSERVATIONS AND RESULTS ON PRE-MAIN SEQUENCE STARS

Catherine L. Imhoff
Astronomy Programs
Computer Sciences Corporation

ABSTRACT

IUE has given us our first good look at the ultraviolet spectra of pre-main sequence objects. This review concentrates on the observations and results obtained for the T Tauri stars and related objects. The T Tauri stars represent a normal phase of pre-main sequence evolution for solar mass stars. As such they provide an invaluable probe of the physical mechanisms involved in star formation and the genesis of stellar magnetic fields and surface activity.

Ultraviolet studies of the T Tauri and related stars have been concentrated in four areas. First, the very strong Mg II emission lines have been observed in order to determine fluxes, line profiles, and variability. Most evidence points to the formation of these strong lines in an extended atmosphere and/or wind. Second, the far-ultraviolet emission lines have been observed to provide diagnostics of the hotter atmospheric regions. The behavior of these lines is very similar to that of the most active late-type stars, lending credence to the belief that many of the T Tauri characteristics are the result of high levels of surface activity. Third, the ultraviolet continuum, which originates largely in the chromosphere, shows potential as a chromospheric diagnostic. Finally, observations of related objects may be used to gain insight into the evolutionary changes occuring during pre-main sequence evolution.

INTRODUCTION

The IUE satellite has proven an extremely useful tool in studies of pre-main sequence evolution. IUE programs that have contributed to our understanding of star formation include studies of young O stars, T Tauri stars, Herbig-Haro objects, Herbig Ae stars, star formation in other galaxies, and the interstellar medium. This review concentrates on the T Tauri stars and related objects.

The T Tauri stars were recognized some time ago as a class of peculiar variable stars (Joy 1945). They are identified through their visual spectra, which are characterized by strong Balmer line and Ca II H,K emission, often Fe II and [S II] emission, a near-ultraviolet excess, veiling of broad photospheric lines of G, K, and M-type spectra, an infrared excess due to dust emission, and irregular variability of most of these characteristics. The broad resonance emission line profiles are

usually interpreted to indicate significant mass loss. However, various scenarios have been used to explain the T Tauri characteristics, including stellar winds, extended gas envelopes, and accretion (see references in Hartmann 1982; also see DeCampli 1981, Hartmann et al. 1982).

The fundamental interest in the T Tauri stars is due to their unique evolutionary status - they appear to represent a normal phase of evolution for roughly solar-mass stars with ages of a few million years. HR diagrams associate the stars with the earliest visible phases of protostellar evolution (Cohen and Kuhi 1979, Stahler 1983). It has been suggested that the T Tauri phase of evolution is associated with the Hayashi phase, i.e. when the star is fully convective (Jones and Herbig 1979).

The fundamental questions that we seek to answer about the T Tauri stars and related objects are these. (1) Why are their spectra and flux distributions so peculiar? (2) Why are the various classes of related objects (T Tauri stars, FU Orionis stars, post-T Tauri stars) so different? (3) What can be learned from these stars about stellar evolution?

The first reported ultraviolet detection of a T Tauri star was not with IUE but with ANS (deBoer 1977). However it is probably fair to say that this field of study did not exist before the lauch of IUE in 1978. A number of researchers have contributed to the study of the T Tauri stars in the ultraviolet. At the end of this paper, a (hopefully) complete list of references is given for IUE observations of the T Tauri stars. A separate list of references is given for papers referred to in the text of this paper. Please note that in the interest of presenting as much material as possible no figures are reprinted in this article; the figures given here are those not otherwise available in published articles.

EARLY IUE RESULTS

The papers describing the observations from the first few years of IUE represent the pioneering results on the T Tauri stars (see references). These early results are summarized here and elsewhere (Gahm 1981, Giampapa 1983, Giampapa and Imhoff 1984).

The primary early result on the T Tauri stars was that they could be detected by IUE! These 11-13 mag G, K, and M stars would not have been detected if it were not for their extreme UV emission.

The second result was the great strength of the Mg II h,k emission lines at 2800 A. (In our first observing run, Mark Giampapa and I never got an LWR exposure short enough to properly expose the MgII line in RW Aurigae!) The surface flux of Mg II in the T Tauri stars is typically 50 times that of the Sun. About 0.1% of the star's bolometric luminosity is emitted in that pair of lines (Giampapa et al. 1981).

Finally, several high-temperature emission lines were identified in

the far-ultraviolet. These include Si IV, C IV, and sometimes He II and N V. The far-UV spectra of the T Tauri stars were found to be quite similar to the spectra of the active late-type stars observed with IUE. In these latter stars, the far-UV emission lines arise in the chromospheres and transition regions of the stars' atmospheres, originating at temperatures of 6000 K to 2 x 10^5 K. The surface fluxes of the far-UV emission lines in the T Tauri stars are around 3 x 10^3 times those of the Sun. These values are as high and higher than for any other late-type stars. The far-UV emission lines contribute another 0.1% to the stellar luminosity for the T Tauri stars (Imhoff and Giampapa 1982a,b). The higher temperature regions of the atmospheres must be produced by in situ heating, not by coronal conduction, to produce this much emission (Cram et al. 1979).

The similarity of the T Tauri UV spectra to those of the active chromospheric late-type stars has provided the strongest evidence to date that the "T Tauri phenomenon" is primarily related to stellar surface activity. Some interesting differences are seen in the UV spectra of the "extreme" T Tauri stars, i.e. the stars showing the greatest line and continuum emission in the visible. Their far-UV spectra show weakened lines of the high temperature lines. The N V and He II emission lines are not seen, although one might argue that this could be an observational problem with noisy data. More convincingly, the C IV line is definitely weakened relative to Si IV. Since C IV is an intrinsically stronger line than Si IV, C IV is virtually always seen as the stronger line in late-type stars. Yet it is weaker than Si IV in a handful of extreme T Tauri stars. We could explain this only if, for some reason, the maximum temperature reached in the star's atmosphere is around the temperature of formation of Si IV, i.e. 8 x 10^4 K. We hypothesized that the mass loss, or stellar wind, in these stars carries away enough energy to inhibit the temperature rise to a coronal region (Imhoff and Giampapa 1980).

FURTHER STUDIES WITH IUE

These early results stimulated a number of investigations of the T Tauri stars with IUE. These have primarily been concerning with refining our understanding of the T Tauri atmospheres by more detailed investigations and extending the observations to a variety of related objects. These results are summarized below.

MgII h,k Emission Lines

The strong Mg II lines have provided us with a useful diagnositic for the T Tauri chromospheres and winds. If the Mg II line is chromospheric in origin, then one would expect it to be variable due to changes in the surface activity and to the rotation of bright "plages" across the stellar disk. However, repeated observations of DG Tauri show no clear variability greater than 10% (Imhoff and Giampapa 1984b). A similar result is found for the extreme T Tauri star RW Aurigae (see Figure 1). The only divergent

value was obtained when the star was particularly active (Imhoff and Giampapa 1984a). The implication of this lack of variability is that the Mg II emission is being produced in an extended region, perhaps in the expanding atmosphere, or wind, of the stars.

Thanks to the strength of the Mg II emission lines, it has proven possible to study them at high dispersion. Ten stars have been observed at high dispersion; about half of these have been published. The line profiles of the Mg II h,k lines are very reminiscent of the those of the other resonance emission lines, such as H-alpha and Ca II H,K. The lines are broad (several 100 km/sec) and appear to be cut by strong blue-shifted absorption. Variability is seen where more than one set of line profiles have been obtained. Interestingly, the variability seems to occur only in the overall strength of the emission and in the blueward absorption (Imhoff and Giampapa 1984a, Jordan et al. 1982). Again this suggests that the Mg II emisson arises in an extended atmospheric region or wind. It is interesting to note that this same result has been obtained for some other active late-type stars (Baliunas, this volume).

Far-ultraviolet Emission Lines

The far-ultraviolet emission lines provide diagnostics of the chromosphere and transition region in the T Tauri atmospheres. Of special interest are the hotter regions of the atmosphere that are accessible only with IUE. (Note: by "transition region", we here refer to an atmospheric region of around 10^5 K. No particular physical mechanism is implied; conduction from a corona is unlikely to produce this region in the T Tauri stars, especially if some of them don't have coronae!)

As many IUE observers know, the IUE spectra are somewhat noisy. The identification of weak features, especially for long integrations where particle "hits" and camera artifacts affect the image, can be difficult. On the other hand, two of the more interesting high-temperature emission lines in the far-ultraviolet, He II and N V, are intrinsically weak compared to C IV and Si IV. Careful reanalysis of a dozen T Tauri spectra shows that the He II and N V lines are definitely detected in only a small proportion of the dozen stars examined (Imhoff and Giampapa 1984b).

One may compare the relative line strengths of the T Tauri stars to those of other active late-type stars. Ayres, Marstad, and Linksy (1981) showed that the emission lines of the late-type stars tend to correlate well with each other. As one progresses to stars with greater levels of surface activity, all the emission lines become stronger but the higher temperature lines tend to be enhanced even more so. For the moderate temperature lines (OI, Si II, C II), the T Tauri stars follow these relations very well, lying just beyond the highest values for the stars examined by Ayres et al. The T Tauri stars diverge, however, for the He II line (thought to be produced by recombination after X-ray photoionization in many late-type stars), the soft X-rays, and for CIV (not plotted separately by Ayres et al.). This divergence occurs even for T Tauri stars

in which He II and the X-rays have been detected, not just the "extreme" T Tauri stars. Thus the relative weakening of the high temperature regions appears to be a general feature of the T Tauri atmosphere. Such effects are also seen in models of a stellar wind and a deep chromosphere (Hartmann, Edwards, and Avrett 1983).

Because of the long integrations involved, studies of the far-ultraviolet variability of the T Tauri stars are limited. The star RW Aurigae has been observed several times since 1978, encompassing periods when the star was particularly active and when it was not. In Figure 2, the far-ultraviolet spectra of RW Aur are shown for four epochs of observation. These are ranked from top to bottom, from most active to least active and from when the star was brightest to when it was faintest. (Most late-type stars are faintest when most active, due to the dark starspots. The T Tauri stars appear to have "bright" spots, or "superplages", with strong chromospheric continuum emission which affects the visual brightness of the stars.) The variations in the lines are more easily followed in Figure 3, where the individual line fluxes are plotted against the visual brightness of the star (in FES counts). The lower temperature lines of C II and Si II increased proportionally with the FES counts, by a factor of 2.5, but the high temperature lines of Si IV and C IV are proportionally much stronger. Figure 4 depicts the dramatic change in the ultraviolet continuum. These spectral changes - enhancement of the high temperature lines, appearance of a UV continuum - resemble strongly the behavior seen in other late-type stars during flares (Baliunas 1983). The primary difference appears to be in time scale. In most late-type stars, flares occur in minutes or at most hours. The level of activity seen in RW Aur in 1979 appeared to persist over a few days. Thus a region of flaring activity, rather than a single flare, may have been involved.

It is clear from a number of lines of evidence that atmospheric motions - winds and turbulence - are very important in understanding the structure of the T Tauri atmospheres. Line profiles for the Balmer lines, Na I D lines, Ca II H,K, and Mg II h,k have been obtained, but all of these lines arise in relatively low temperature regions. A particularly useful observation would be line profiles for the high temperature lines. Since the integration time for these lines in low dispersion is at best 3 hours, few such observations have been attempted. Penston and Lago (1982) have reported one successful observation of the far-ultraviolet emission lines of RU Lupi, another extreme T Tauri star. The lines are relatively broad, about 350 km/sec. The C IV line profiles, though noisy, appear to show blueward emission up to -150 km/sec from the rest velocity.

The UV Continuum

In the T Tauri stars, the ultraviolet continuum seems to be largely produced in the chromosphere (Calvet et al. 1984). This then provides us with a new chromospheric diagnostic. The continuum fluxes may be compared with the newly available model calculations.

Since the UV continuum is relatively easily observed with IUE with integrations of less than an hour, it can be used to study the variability of the stars with reasonably good time resolution and better accuracy than can be obtained with IUE data for single emission lines at low dispersion. Recall that the Mg II lines do not show much variability. However, the UV continuum can show dramatic variability (as seen in Figure 4). We have recently observed several T Tauri stars with IUE in coordination with the photometric monitoring program of Eric Rydgren and Fred Vrba. Our preliminary results indicate that the UV continuum variations matched the visual continuum variations seen over the rotation of the stars. This confirms that the emission arises in the same or related regions of the atmosphere, suggesting that further use may be made of the UV continuum to help us to understand the T Tauri stars.

Related Pre-Main Sequence Objects

In addition to the T Tauri stars, there are several other members of the "pre-main sequence zoo". The objects are generally distinguished by some unique observational characteristics, but ultimately we would like to fit them into the evolutionary scheme of things.

Recent results on bipolar flows, jets, and Herbig-Haro objects indicate that some very energetic events are associated with the earliest stages of evolution of a protostar. The scenario is not yet entirely clear, but these energetic ejection events appear to be associated with the earliest part of the T Tauri phase and even the "pre-T Tauri" phase, when the protostar is still heavily embedded in its natal cloud of dust and gas.

FU Orionis is a pre-main sequence object that brightened by over 5 magnitudes in 1936. A similar nova-like brightening was seen in 1969 in V1057 Cygni. In the latter case, pre-outburst observations indicated that the progenitor was a faint pre-main sequence star with T Tauri characteristics. A statistical analysis by Herbig (1977) showed that in all likelihood such outbursts are quite common during a T Tauri star's lifetime - an outburst every 10^4 years, or 500 outbursts in a lifetime of 5 x 10^6 years. Some confirmation of this idea is found in the expanding shells seen in the Na I D line profiles of several T Tauri stars (Mundt 1982). The nature of the outburst is not well understood (Larson 1980).

We have obtained several spectra of FU Orionis with IUE. Among these are two high dispersion spectra yielding the Mg II emission line profiles. The broad emission components of the h and k lines do not appear particularly remarkable, until one realizes that the emission is nearly all redward of the rest velocity. This does not appear to indicate mass infall, however. Observations of the H-alpha and Na I D lines indicate a very strong stellar wind (Hartmann 1983). Thus the redward emission of the Mg II lines appears to correspond with the emission portion of pronounced P Cygni line profiles. The blueward absorption is not seen because the ultraviolet continuum is very weak in these high dispersion spectra. Thus, after almost 50 years, FU Orionis continues to lose mass in a strong

stellar wind.

The heavily embedded, very young protostars would not appear to be good candidates for IUE observations. An object obscured by 5 magnitudes of visual extinction experiences a factor of about 10^5 attenuation around the C IV line. The Cohen-Schwartz star is such an embedded T Tauri star that has been identified as the source of Herbig-Haro objects 1 and 2. Observations of this star with IUE unexpectedly turned up a weak, extended UV continuum (Bohm and Bohm-Vitense 1982). However Witt and Mundt (1983) have argued convincingly that the weak continuum is due to the Orion reflection nebulosity. Additional IUE observations obtained of the Orion nebula near the star confirm this explanation (Witt 1983).

This result did not deter investigators when the infrared object IRS 8 associated with Herbig-Haro 57 was reported in outburst. Three groups of researchers (Bohm, Bohm-Vitense, Maran, Stecher, Michalitsianos, Kalinowski, and Imhoff) teamed up to obtain a long integration on the short wavelength camera at IRS 8-HH 57. Nothing was detected.

Studies of solar-like main sequence stars have been very successful in finding correlations of stellar surface activity with the age of the star. In addition to earlier work with the Ca II H,K emission lines (e.g. Skumanich 1972), age relations have been found for ultraviolet chromospheric and transition-region lines from IUE data (Boesgaard and Simon 1982, Simon and Boesgaard 1983). Most of the available data are for stars older than 10^8 years. The T Tauri stars have ages around a few million years. Thus there is a gap in our age coverage between the T Tauri stars and the main sequence. Protostars at this stage of evolution (known as "post-T Tauri" stars; Herbig 1973) apparently resemble normal stars in most of their observational characteristics, so few of them have been found. An unexpectedly good method of finding them has been in the X-ray region of the spectrum, where the stars are quite luminous.

A handful of post-T Tauri stars have been observed with IUE. The LWR spectrum of HD 283572 shows a photospheric continuum and weak Mg II emission barely rising above the continuum in low dispersion. The far-ultraviolet spectrum of this post-T Tauri star has been obtained by Walter (1983). As in many other active late-type stars, C IV is the strongest line and He II and N V are clearly seen. Thus in the ultraviolet, this star appears to be intermediate in its characteristics between the T Tauri stars and the young main-sequence stars.

The interesting aspect of all of this is that there is no strong evidence that the known post-T Tauri stars are in fact older or more evolved than the T Tauri stars. If they are placed in the H-R diagram, they fall in a portion of the region occupied by T Tauri stars (albeit at the "bottom" of the convective tracks). The strength of the lithium line, often used as an age indicator, does not distinguish the two groups of stars. If one then hypothesizes that the stars all represent the same evolutionary stage, then one must explain the strong differences among the

stars. It is difficult to explain the higher surface activity of the T Tauri stars with the dynamo effect, since the post-T Tauri stars rotate at least as fast as the T Tauri stars (unless one invokes some other parameter such as convective envelope depth or differential rotation). This question may be expected to keep the pre-main sequence evolution observers and theorists busy for some time.

SUMMARY

Most of the IUE research on the T Tauri stars has focussed on the first of the "big questions" - why are the T Tauri stars so strange? The answer appears to be that they are not so strange. Their UV spectra have demonstrated the similarities of the T Tauri stars to other active late-type stars. The spectral peculiarities seen in the visual appear to be secondary effects produced by the very high level of surface activity evident in the ultraviolet.

The evolutionary questions are more difficult to answer. At present it is not possible to assign a unique age to any given protostar; thus no evolutionary sequence can be reliably constructed from the available data. However, it is tempting to create a hypothetical scenario such as the following. An embedded protostar accretes matter, giving rise to various eruptive events such as FU Orionis-type outbursts and the creation of Herbig-Haro objects and jets. As the circumstellar disk thins, the star becomes visible as a T Tauri star. A high level of surface activity is seen due to strong magnetic fields, which may be primordial and/or produced through a dynamo associated with the deep convective zone and rotation. Waves generated in the convective zone heat and extend the atmosphere, where at the cooler temperature zones emission lines radiate away much of the energy. However at around 10^5 K a wind may carry off a significant amount of the energy. As time goes by the convective zone shrinks, the level of activity decreases, and the atmospheric densities decrease. The non-radiative energy builds up in the atmosphere, which can now reach coronal temperatures. At this point the protostar's atmosphere has become structurally very similar to a main-sequence star.

I would like to thank Mark Giampapa, my collaborator on our IUE studies of the T Tauri stars. In addition, I would like to thank the IUE Project and Observatory personnel for their encouragement and support over the last ten years. This work was performed with the support of NASA contract NAS 5-25774.

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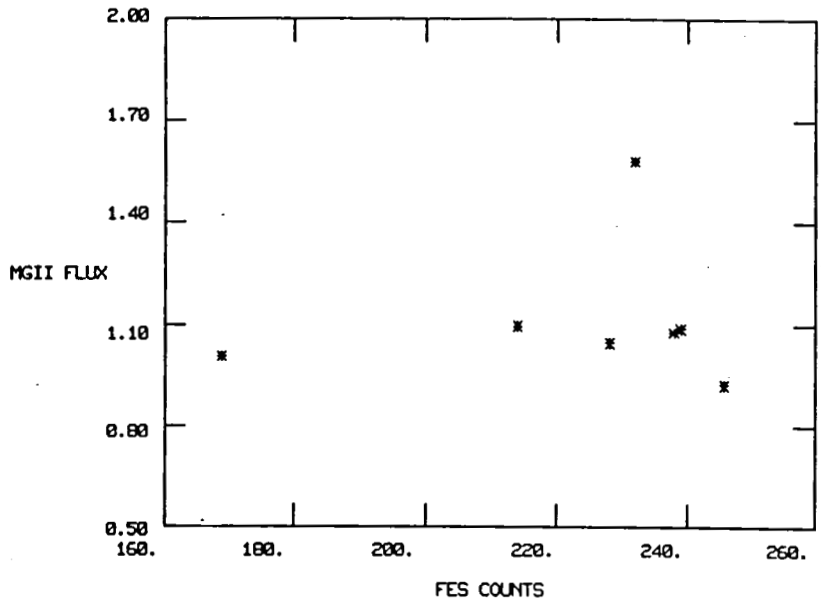

Figure 1. Observed Mg II flux (10^{-11} erg/cm^2/sec) versus visual brightness (FES counts) for several observations of RW Aur.

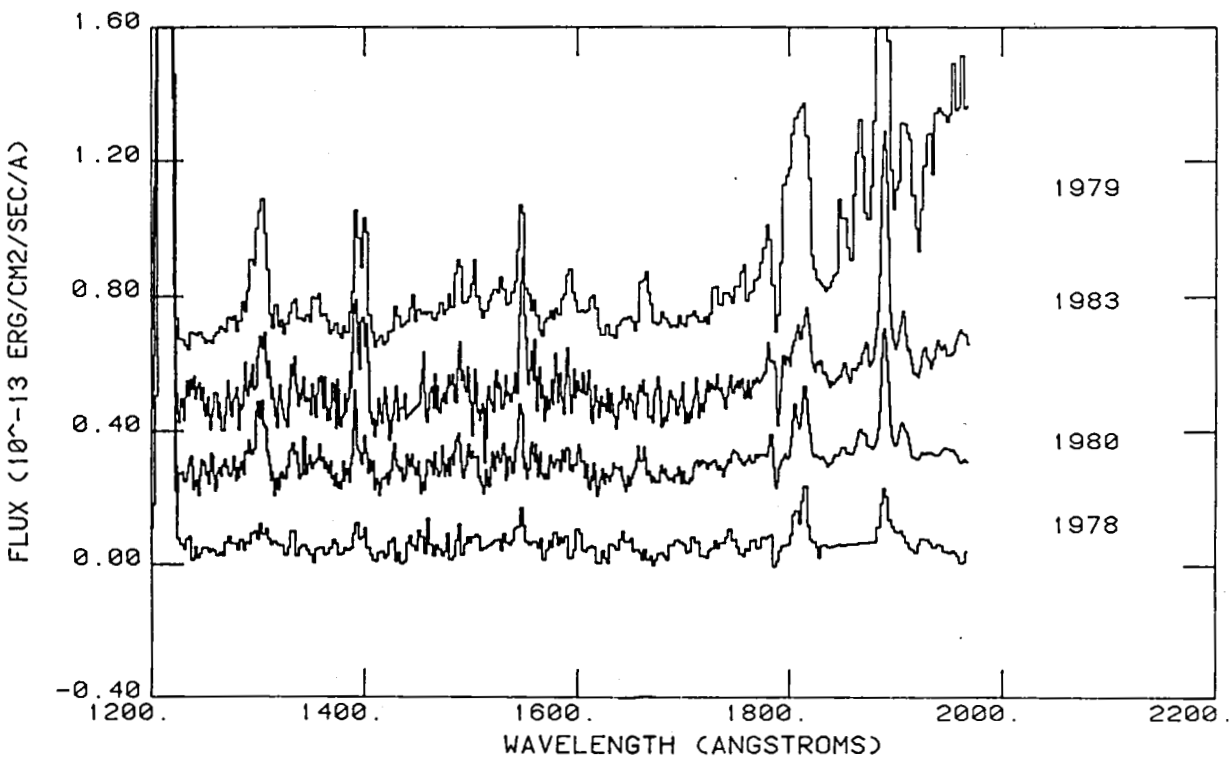

Figure 2. Four SWP spectra of RW Aur, each offset by 0.2 x 10^{-13} in the vertical axis. The strongest emission lines are O I 1300, Si IV 1400, C IV 1550, Si II 1815, and Si III 1892.

Figure 3. Variation of ions formed at various temperatures versus visual brightness for the four SWP spectra of RW Aur.

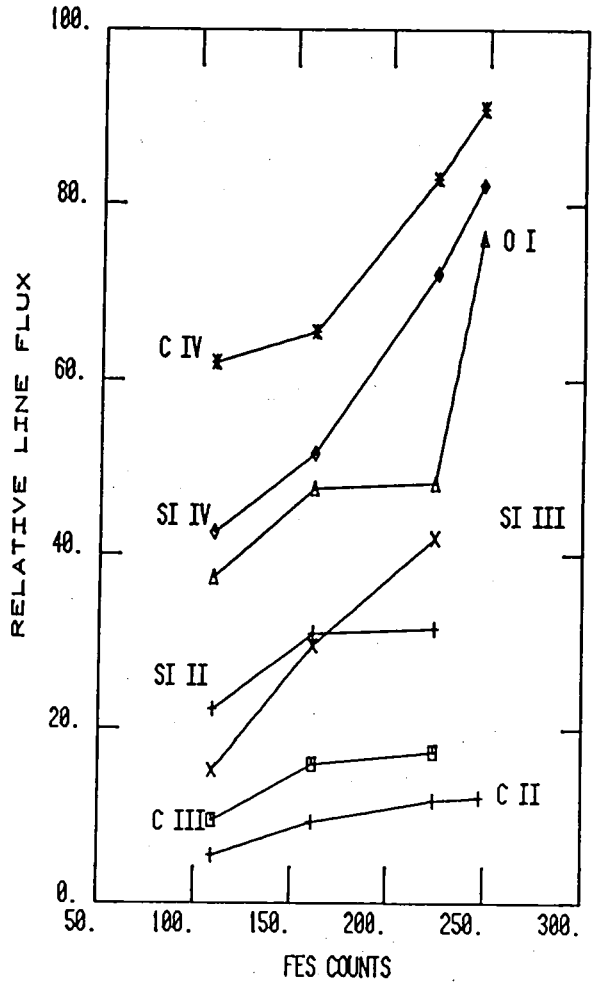

Figure 4. Variation in the UV continuum in RW Aur.